WHOLE-SUBSTRATE SPECTRAL IMAGING SYSTEM FOR CMP

INVENTORS

SCOTT A. CHALMERS

RANDALL S. GEELS

THOMAS F. A. BIBBY

This application claims the benefit of U.S Provisional Application No. 60/459,876 filed April 1, 2003, and U.S. Provisional Application No. 60/469,449, filed May 5, 2003, each of which is hereby fully incorporated by reference herein as though set forth in full.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention pertains to in situ metrology during chemical-mechanical planarization (CMP). More particularly, it pertains to a method and apparatus for monitoring a film on a substrate as it is planarized.

2. Related Art

Chemical-mechanical planarization (CMP) has emerged as the dominant technology for minimizing surface topology during the manufacture of integrated circuits. By minimizing surface topology, the entire surface can be arranged to be within the depth of field of lithography tools, which results in significantly reduced feature dimensions and a dramatic rise in the value of devices made with such features.

The basic concept of CMP is to press a substrate against a polish pad in the presence of a slurry and relative motion between the substrate and the polish pad. This

combination causes "high" regions to abrade more quickly than "low" regions. Over time, the "high" regions are abraded away leaving a very flat surface. The flatness of such a surface depends in part on the composition of the substrate. If the substrate is completely homogeneous, then the surface can become extremely flat. However, if there are structures present in the substrate, such as metal lines embedded in a dielectric film (formed using a so-called damascene process), exposure of such metal lines during CMP can lead to significant variation in etch rate depending on the exposed materials.

CMP is used for planarizing both metal and dielectric film stacks. Examples of metal stacks include tungsten over titanium nitride over titanium, and copper over tantalum over tantalum nitride. Examples of dielectric film stacks include front-end of the line structures such as shallow trench isolation and back-end of the line inter-level dielectric films on top of metal lines.

Whether planarizing metal or dielectric stacks, the ability to monitor the polishing process, and the ability to stop polishing at the appropriate time, are critical aspects of quality control. If polishing a metal film, incomplete polishing results in regions of residual metal, which causes electrical shorts and device failures. Excessive polishing of metal films causes erosion of underlying dielectric layers, which can dramatically degrade device performance due to increased circuit capacitance. Likewise, incomplete or excessive dielectric planarization also causes problems. Incomplete planarization results in excessive residual topology, which causes poor feature definition during lithographic exposures and therefore results in poor yield. Excessive planarization causes dishing and increased capacitance, which also degrades circuit performance. Differential material removal rates across a substrate being polished causes non-uniformity that also contributes to poor performance. Finally, the inability to compensate for overall substrate polish non-uniformity prevents optimum performance.

To overcome these limitations many techniques have been proposed to provide a stable CMP process. These techniques fall into two broad categories: local endpoint detection techniques and global endpoint detection techniques. Global endpoint detection systems measure a single aspect of a CMP process, and infer the condition of the

substrate across the entire surface being polished. Repeated measurements provide a time dependent global signal representative of the progress of the polish process. The most significant advantage of global endpoint detection techniques is that they provide an indication of the status of the polish process across the entire substrate. One such technique generates an endpoint signal by polishing a blank substrate, determining an etch rate, and then calculating a polish time based on a known thickness of film to be removed, and on the etch rate. However, this technique suffers from being very susceptible to variations in the etch rate as the polish pad ages and wears out. This, and other global endpoint detection techniques also suffer from providing no information about individual sites on the surface of the substrate during the polish process.

Local endpoint detection systems sense the surface of a small portion of a substrate during the polish process and infer global properties based on this measurement. Typically, such measurements involve multiple such measurements and result in some limited information about the condition of the substrate at the time of the measurement. For example, one technique uses a sensor that sweeps across a substrate and makes measurements to produce a diameter scan. However, this technique suffers from being unable to accurately infer the condition of the substrate across the entire surface being polished, i.e., where measurements are not being made.

Both local and global endpoint detection approaches can provide valuable information about the polish process. However, there is no system currently available that offers the benefits of both types of systems.

Furthermore, as device geometries and edge exclusion zones (the un-usable periphery of a substrate) shrink, there is a growing need for detailed, quantitative information about the condition of all points on a substrate during the polish process, not just at the end of the polish process. Such information is essential not only for understanding how the polish process evolves, but more importantly for use in adjusting polish parameters during the polish process to optimize polish uniformity within a substrate and from substrate to substrate. One specific application involves multi-zone carriers. Such carriers apply differential pressure to different portions of the substrate to

compensate for non-uniformities in the polish process, and require feedback to know how much pressure each zone should apply to produce an optimally polished substrate.

One proposed global endpoint technique for monitoring and controlling CMP processes to measure the motor current of the carrier and platen used to cause relative motion between the substrate and the polish pad. United States Patent 5,069,002 describes this global endpoint detection approach. As the material being polished clears and a different material is exposed, differences in friction cause a change in motor current that can be detected. For some applications this approach has met some success. However, this approach suffers from a dependence on polishing materials having very distinct friction against the polish pad being used. As a global endpoint detection technique, this approach provides no information about planarization at any particular location on a substrate being planarized.

Yet, another proposed global endpoint detection technique involves measuring the capacitance of the wafer against the polish pad during the polish process, as described in United States Patent 5,081,421. However, this approach has proven to depend strongly on the pattern of structures formed on substrates being polished. It has also involved a very poor signal to noise ratio, and provides no local polish process information.

Numerous approaches based on acoustical methods have also been proposed including United States Patent No. 5,876,265, United States Patent No. 5,240,552, United States Patent No. 5,245,794, United States Patent No. 5,222,329, United States Patent No. 5,399,234, and United States Patent No. 5,196,006. These patents describe approaches that assess the overall surface of the substrate being polished, but suffer from being unable to provide locations specific process information. In addition, these approaches are not production worthy and require sophisticated expertise to use.

Numerous optically based techniques have also been proposed for monitoring in situ CMP process performance, and in particular for detecting endpoint during a CMP process. All of these techniques are local endpoint detection techniques and involve shining light at a substrate being planarized and monitoring either reflected or transmitted light. These techniques further involve sensing light reflected from one or more points

on a wafer, and inferring endpoint based on these measurements. These techniques involve making measurements serially, and at one location at a time.

Several proposed techniques use single wavelength light, e.g. light from a laser source, and monitor the intensity of reflected light. One particular technique, described in United States Patent No. 6,494,766, involves scanning a single light source across a wafer to obtain a plurality of measurements, partitioning these measurements into radial components, and inferring endpoint based on these measurements. Although this approach does provide a diameter scan, it suffers from providing no information about areas away from the diameter line being measured. This approach further suffers from an inability to detect whether a substrate has slipped during polish, which can be a serious process issue. Other techniques exploit the information available in a broad spectrum, e.g. visible light. However, all of these techniques provide extremely limited information about the planarization process across the entire substrate.

An additional limitation of these optical techniques is that they are sensitive to signal noise created by light scattering from feature edges. Such diffraction effects are known to have both wavelength and angular dependence, and can substantially affect spectral profiles.

United States Patent 5,949,927 describes a technique and apparatus for the optical monitoring and measurement of a thin film (or small region on a surface) undergoing thickness and other changes while it is rotating. As such, it is a local endpoint detection system. However, this invention does not address the issue of assessing light scattered and/or diffracted from patterned features. The patent purports to allow measurements to be made on fixed, selected portions of a wafer, but does not describe how arbitrary, pre-determined site can be selected. Other optical endpoint patents, such as the abovementioned '766 patent suffer from the same limitation. Sites that do not pass over the fixed-location sensor cannot be measured. Furthermore, incidental substrate rotation during the polish process would cause measurements to be erroneous. Thus, this patent does not address global endpoint detection needs.

An additional challenge of optical endpoint detection systems relates to the multiplicity of film stacks likely to be present during CMP. Stationary metrology systems such as those manufactured by companies such as KLA-Tencor, Thermawave, and Rudolph Technologies address this issue by positioning each substrate on a vibrationally isolated platform, and focusing light to a spot as small as 10 um. This combination ensures that sensed light corresponds to light reflected from a single film stack. Substrates being polished on CMP tools are in motion and immersed in slurry, which is translucent. The motion of the substrate causes light to scan across multiple film stacks, which significantly affects the measured spectral response and complicates signal analysis.

Developments in recent years have led to an increased need for precise control over the planarization process. The use of copper for increased conductivity of electrical interconnects requires the use of ultra-thin barrier metals. However, slurries suitable for planarizing copper do not work well on the barrier metals, so processes using multiple slurries have been developed. These processes require extremely precise control over when a first slurry is changed to a second slurry to avoid either regions of un-cleared metal or regions of over-polished metal.

SUMMARY OF THE INVENTION

According to a first aspect of this disclosure, a whole-substrate imaging system is described. In this system, a carrier holds a substrate, with the substrate having a pad-contacting surface with a maximum planar dimension. A rotating platen has a radius and holds a polishing pad, with the platen including a slit having a length substantially disposed along its radius and equal to or exceeding the maximum planar dimension of the substrate. The platen includes an optically transparent element located at about the slit. A frame operatively disposes the rotating platen relative to the carrier, such that the pad-contacting surface of the substrate contacts the polishing pad, and substantially completely traverses the slit within a rotation of the platen. An image processing subsystem captures, from light reflected from the pad-contacting surface and transmitted through the optically transparent element, a plurality of one-dimensional images

representative of the substantial entirety of the pad-contacting surface of the substrate during traversal of the pad-contacting surface past the slit. It then derives therefrom a a two-dimensional image, or frame, comprising frame data providing information about the substrate useful for subsequent chemical-mechanical processing of the substrate.

According to a second aspect of this disclosure, a method of imaging a substrate is described. In this method, a substrate is held, the substrate having a pad-contacting surface with a maximum planar dimension. In addition, a polishing pad is held by a rotating platen having a radius and including a slit having a length substantially disposed along the radius and equal to or exceeding the maximum planar dimension of the substrate. The platen includes an optically transparent element located at about the slit. The rotating platen is operatively disposed relative to the pad-contacting surface, such that the pad-contacting surface of the substrate contacts the polishing pad, and substantially completely traverses the slit within a rotation of the platen. A plurality of one-dimensional images representative of the substantial entirety of the pad-contacting surface of the substrate is captured from light reflected from the pad-contacting surface and transmitted through the optically transparent element during traversal of the pad-contacting surface past the slit. A frame is derived from the plurality of one-dimensional images. The frame comprises frame data providing information about the substrate useful for subsequent chemical-mechanical processing of the substrate.

According to a third aspect of this disclosure, a method of forming a fiber assembly is disclosed. In this method, an inner surface of a first plate is patterned with substantially parallel grooves, with the first plate having an outer surface. Individual sensory optical fibers are placed in separate ones of the grooves and secured. An inner surface of a second plate is positioned over the sensory fibers as positioned in the grooves of the first plate, with the second plate having an outer surface. The inner surfaces of the first and second plates are secured together. Illumination optical fibers are positioned on the outer surface of the first plate substantially in parallel with the sensory fibers and secured. Similarly, illumination optical fibers are positioned on the outer surface of the second plate substantially in a parallel with the sensory fibers and secured. The ends of

the sensory and illumination fibers are then processed to be substantially co-planar with one another.

According to a fourth aspect of this disclosure, a method of forming a fiber assembly is disclosed. In this method, sensory optical fibers are positioned substantially in parallel with one another on an inner surface of a first plate, with the first plate having an outer surface. The sensory fibers as positioned on the inner surface of the first plate are then secured. An inner surface of a second plate is positioned over the sensory fibers as positioned on the inner surface of the first plate, with the second plate having an outer surface. The inner surfaces of the first and second plates are secured together. Illumination optical fibers are positioned on the outer surface of the first plate substantially in parallel with the sensory fibers and secured. Similarly, illumination optical fibers are positioned on the outer surface of the second plate substantially in a parallel with the sensory fibers and secured. The ends of the sensory and illumination fibers are then processed so that the same are substantially co-planar with one another.

According to a fifth aspect of this disclosure, an optical fiber assembly is disclosed. The assembly includes a fiber assembly element. A first bundle of illumination fibers is also included. The illumination fibers each have ends which substantially terminate at the fiber assembly element and which are arranged in at least one first and at least one second rows. A second bundle of sensory fibers is also included. The sensory fibers have ends which substantially terminate at the fiber assembly element and which are arranged in a third row between the first and second rows.

According to a sixth aspect of this disclosure, an optical fiber assembly is disclosed. The assembly includes a fiber assembly element. A first bundle of illumination fibers is also included. The illumination fibers each have ends which substantially terminate at the fiber assembly element and which are arranged in first and second rows. A second bundle of sensory fibers is also included. The sensory fibers have ends which substantially terminate at the fiber assembly element and which are arranged in a third row between the first and second rows.

According to a seventh aspect of this disclosure, a die imaging system is described. In this system, a carrier holds a substrate, with the substrate having a pad-contacting surface with a maximum planar dimension and, on one side of the substrate, partially processed integrated circuits separated by streets. A partially processed integrated circuit together with surrounding streets forms a die. A rotating platen has a radius and holds a polishing pad, with the platen including a slit having a length substantially disposed along its radius and approximately equal to the maximum planar dimension of the die. The platen includes an optically transparent element located at about the slit. A frame operatively disposes the rotating platen relative to the carrier, such that the pad-contacting surface of the substrate contacts the polishing pad, and substantially completely traverses the slit within a rotation of the platen. An image processing subsystem captures, from light reflected from the pad-contacting surface and transmitted through the optically transparent element, a plurality of one-dimensional images representative of the substantial entirety of the pad-contacting surface of the substrate during traversal of the pad-contacting surface past the slit. It then derives therefrom a frame comprising frame data providing information about the substrate useful for subsequent chemical-mechanical processing of the substrate.

Many advantages are realized by the present invention. One advantage is that it compensates for the wavelength dispersive effects of diffraction occurring at feature edges on integrated circuits. A second advantage of the present invention is that it allows measurement site sizes to be smaller than those defined by the geometry and numerical aperture of the sensing fiber. Another advantage is that it provides for spectral analysis methods based on broadband or narrow band light. Another advantage is that it allows measurements to be made for a variable polish pad thickness.

Many other advantages of the present invention flow from its ability to allow measurements of thin-film stacks across an entire substrate. One such advantage is that the present invention provides an image of the entire substrate. Another advantage is that it allows measurements to be made over multiple film stacks across an entire substrate. Another advantage is that it provides measurements of metal clearing and non-uniformity measurements across an entire substrate throughout metal CMP processes. Another

advantage is that is provides residual film thickness and non-uniformity measurements across an entire substrate during and at the conclusion of dielectric CMP.

Yet another advantage of the present invention is that it provides residual film thickness and non-uniformity measurements in selected regions across a substrate during and at the conclusion of dielectric CMP. Another advantage of the present invention is that it provides substrate measurements suitable for feedback to a CMP carrier with one or more pressure zones. Another advantage is that it provides substrate measurements suitable for feedback to a CMP run-to-run control system. Yet another advantage of the present invention is that it provides a way to obtain images of portions of a substrate being polished. Another advantage of the present invention is that it provides a way to obtain images of whole and/or partial die on portions of a substrate being polished.

Other systems, methods, features and advantages of the invention or combinations of the foregoing will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features, advantages and combinations be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows one embodiment of a whole-substrate imaging system on a CMP tool according to the invention.

FIG. 2A shows one embodiment of the surface of a platen with a slit for viewing a substrate during polishing.

FIG. 2B shows a schematic representation of one embodiment of a layout of components of a whole-substrate imaging system according to the invention.

FIG. 3 shows an alignment of one embodiment of a fiber assembly within the slit of a platen for viewing a substrate during CMP.

FIG. 4A shows a top view of the fiber assembly of FIG. 3.

FIG 4B shows a detailed view of illumination and sensing fibers of FIG. 3.

FIG. 5 shows an embodiment of a line-scan spectrometer.

FIGS. 6A-6E show a layout of illumination and sensing fibers of a fiber assembly according to one embodiment of the invention.

FIGS. 7A-7C show an alternate layout of illumination and sensing fibers of a fiber assembly.

FIG. 8 illustrates one embodiment of a method of acquiring and processing spectral reflectance data using a system according to the invention.

FIGS. 9A-9C illustrate an apparatus according to the invention the operation.

FIG. 10 shows an image of a substrate during CMP.

FIG. 11 shows a whole-die imaging system on a CMP tool according to the invention.

FIG. 12A shows a surface of a platen having a slit for viewing a substrate during a CMP process according to the invention.

FIG. 12B is a schematic representation of one embodiment of a layout of components of a whole-die imaging system according to the invention.

FIG. 13 shows a swath corresponding to a die-sized optical assembly as it traverses a substrate.

FIG. 14 illustrates one embodiment of a method according to the invention for acquiring and processing spectral reflectance data using a whole-die imaging system.

FIG. 15A shows a swath of data acquired by means of the invention.

FIG. 15B shows a die having an optical difference in one quadrant.

FIG. 15C shows an intersection of a street and a transverse street with an optical difference in an adjacent die quadrant.

FIG. 16 illustrates an embodiment of a line imaging spectrometer.

DETAILED DESCRIPTION

As utilized herein, terms such as "about" and "substantially" and "near" are intended to allow some leeway in mathematical exactness to account for tolerances that are acceptable in the trade. Accordingly, any deviations upward or downward from the value modified by the terms "about" or "substantially" or "near" in the range of 1% to 20% should be considered to be explicitly within the scope of the stated value.

As used herein, the term "software" includes source code, assembly language code, binary code, firmware, macro-instructions, micro-instructions, or the like, or any combination of two or more of the foregoing.

The term "memory" refers to any processor-readable medium, including but not limited to RAM, ROM, EPROM, PROM, EEPROM, disk, floppy disk, hard disk, CD-ROM, DVD, or the like, or any combination of two or more of the foregoing, on which may be stored a series of software instructions executable by a processor.

The terms "processor" or "CPU" refer to any device capable of executing a series of instructions and includes, without limitation, a general- or special-purpose microprocessor, finite state machine, controller, computer, digital signal processor (DSP), or the like.

The term "logic" refers to implementations in hardware, software, or combinations of hardware and software.

The term "CMP" means chemical mechanical planarization, or, more generally, any chemical mechanical processing performed on a semiconductor substrate.

The apparatus of the present invention is a whole-substrate imaging system 105 that allows a substrate 180 to be monitored during a polish chemical-mechanical

planarization process. FIG. 1 shows whole-substrate imaging system 105 that includes a platen 120 with a slit 130, a fiber assembly 125 disposed within slit 130, and an optoelectronic assembly 115 that is optically coupled to fiber assembly 125 via illuminator bundle 174 and sensor bundle 172. Whole-substrate imaging system 105 further includes an electrical connector 176, a rotating coupler 110 and an electrical connector 177, which are electrically connected in series so that optoelectronic assembly 115 is electrically connected to a system controller 108. System controller 108 and electrical connector 177 are located remotely from platen 120.

Whole-substrate imaging system 105 is used in a CMP tool 100 that further includes a polish pad 135 mounted on platen 120, a motor (not shown) that causes platen 120 to rotate about axis of rotation 150 at a platen rotation rate, a carrier assembly 170 rotated by a second motor (also not shown) about axis of rotation 155 at a carrier rotation rate. Axis of rotation 155 is offset from axis of rotation 150 by a distance R_{OFFSET}, which may vary with time. Carrier assembly 170 includes a retaining ring 182 that secures substrate 180 in place during the polish process. A slurry delivery system (not shown) provides slurry to polish pad 135 near axis of rotation 150 so that centrifugal forces disperse the slurry over polish pad 135. A CMP system controller (not shown) controls the operation of the CMP tool.

Substrate 180 is preferably a semiconductor wafer having a center and a diameter with partially formed elements of an integrated circuit formed on one side. The partially formed elements include at least one film stack to be planarized. Example film stacks include copper with a tantalum under-layer, tungsten over titanium nitride over titanium, silicon dioxide, and spin-on-glass (SOG). Substrate 180 may be formed from materials such as silicon, gallium arsenide, gallium antimonide, or other III-V materials. Substrate 180 may also be formed from II-VI materials such as HgCdTe. In addition, substrate 180 may be formed of any of a wide variety of glasses such as BK7, flint glasses, and fused silica, or plastics such as polymethylacrylate, polycarbonate, etc. Substrate 180 may also be a partially formed flat panel display.

Platen 120 is a disk having a working face 122 with a radius that is larger than the diameter of substrate 180. Preferably, platen 120 is a solid disk except for portions the disk that have been removed to accommodate whole-substrate imaging system 105. However, it is not necessary that the disk be solid to practice this invention. Other arrangements such as a hollow disk or a thin, solid disk over a honeycomb core also work. Additionally, slit 130, which is shown throughout the many figures as being cut into platen 120 in a generally rectangular form, is not restricted to a rectangular form in the present invention. Slit 130 comprises an opening in platen 130, which opening may comprise any shape through which light may pass for the purposes of capturing reflectance data from a substrate 180. Accordingly, slit 130 may be rectangular, circular, oblong, symmetrical, asymmetrical, or any other shape.

Rotating coupler 110, such as a Mercotac Connector from Mercotac, Inc. (Carlsbad, California), serves to allow electrical signals to be exchanged between optoelectronic assembly 115 and system controller 108.

Electrical connector 176 and electrical connector 177 include wires that deliver synchronization and control signals, as well as power, to optoelectronic assembly 115. Electrical connector 176 and electrical connector 177 further include wires that deliver a video signal from optoelectronic assembly 115 to system controller 108.

Polish pad 135 may be an IC1000 from Rodel Corp. (Wilmington, DE), has an optical element (or window) 137 that transmits light, and attaches adhesively to working face 122 of platen 120. Window 137 is transparent, and in one embodiment, may be formed from JR111 material from Rodel Corp.

Optoelectronic assembly 115 generates light that propagates into illuminator bundle 174, and receives light from sensor bundle 172, which optoelectronic assembly 115 converts to an electrical signal. The electrical signal is directed to rotating connector 110 via electrical connector 176 for use by the system computer. This electrical signal can be structured to represent the image of substrate 180, or it can be structured to signal the CMP system controller to stop polishing or to go to the next polish step.

Illuminator bundle 174 is a bundle of optical fibers that serve couple light from optoelectronic assembly 115 to fiber assembly 125. Sensor bundle 172 is a bundle of optical fibers that serve to couple light reflected from substrate 180 to optoelectronic assembly 115.

System controller 108 includes a computer that has a video frame grabber, and that interfaces with the CMP system controller. The CMP system controller provides information such as the rotation rate of platen 135, the rotation rate of carrier 170, and the distance of R_{OFFSET}, to system controller 108. Based on this information, system controller 108 generates an angle reference signal needed to allow optoelectronic assembly 115 to collect reflectance data when fiber assembly 125 is beneath carrier 170.

System controller 108 further includes a variable power supply controlled by the computer. The variable power supply may comprise a Schott-Fostec Model DCR® III (Schott-Foster, Auburn, NY) illuminator for fiber optic cables, to which functionality of the light bulb has been removed to optoelectronic assembly 115 in platen 135. The variable power supply generates a power and control signal that is communicated to optoelectronic assembly 115 via connector 177, rotating coupler 110, and connector 176. The power and control signal has a voltage that varies from 9 to 21 volts, and serves to provide power for optoelectronic assembly 115 and to regulate light generated by optoelectronic assembly 115.

In operation, a substrate 180 loaded into carrier assembly 170 is pressed into polish pad 135 while carrier assembly 170 rotates about axis of rotation 155, platen 120 rotates about axis of rotation 150, and slurry flows across polish pad 135. A combination of chemical and mechanical processes abrades material from the surface of substrate 180. While the polishing process takes place, optoelectronic assembly 115 generates light based on the power and control signal generated by the variable power supply generator within system controller 108. This light passes through optical illuminator bundle 174 to fiber assembly 125, where it illuminates wafer 180 as slit 130 passes under wafer 180. Fiber assembly 125 also receives light reflected from wafer 180, and directs this reflected light into sensor bundle 172. Optoelectronic assembly 115 receives the reflected light

and converts it into the video signal than can be converted into an image of substrate 180 by system controller 108.

FIG. 2A shows a schematic representation of working face 122 of platen 120, and the position of fiber assembly 125 in slit 130. FIG. 2B shows a schematic representation of optoelectronic assembly 115 within platen 120. Optoelectronic assembly 115 includes a controller 195, a light source 160, a spectrometer 190, connector 182, and connector 184.

Slit 130 extends from near rotational coupler 110 radially outward. Slit 130 is longer than the diameter of substrate 180, and allows R_{OFFSET} to be varied to meet CMP process requirements. Slit 130 is approximately 2 mm wide in a preferred embodiment, but only needs to be wide enough to allow light from the illumination fibers and to the sensors fibers to pass unobstructed. Slit 130 should be at least as long as the wafer diameter plus any required additional length to accommodate wafer misplacement or motion associated with R_{OFFSET}. Slit 130 may optionally include a transparent platen window, or transparent element, to ensure fluids do not interfere with the functionality of optoelectronic assembly 115.

Controller 195 provides an interface between system controller 108 and spectrometer 190 and light source 160. Controller 195 is operatively connected to light source 160 via connector 182, which allows controller 195 to control light source 160. Controller 195 is also operatively connected to spectrometer 190 via connector 184. Controller 195 interprets the power and control signal from the variable power supply in system controller 108 as an ON/OFF and intensity control for light source 160. In one embodiment, if the voltage of the power and control signal drops below 10 V, it is interpreted as being in an OFF state, and if the voltage is greater than 10 V, the light is turned on to an intensity proportional to the voltage in excess of 10 V.. Controller 195 further uses the power and control signal to provide power for spectrometer 190 using a DC-DC converter (not shown). The functionality of controller 195 can be implemented using standard electronic components and design techniques well known in the art.

Preferably, light source 160 is a 150W EKE bulb, available from Schott Fostec (Auburn, New York). Light source 160 emits light in a wavelength range from approximately 400 nm to 800 nm. However, the invention can also work if light source 160 is a multiple wavelength source that emits at light at least two discrete wavelengths. In addition, the invention can also work if light source 160 is a single wavelength emitting source such as a laser, provided the light emitted by the laser is not strongly absorbed by the slurry used to polish substrate 180.

Spectrometer 190 includes a wavelength-dispersive element, such as a prism or diffraction grating that separates light reflected from substrate 180 and passed through sensor bundle 172 into its spectral components. Spectrometer 190 converts these spectral components into a video signal that is communicated to system controller 108 via connector 176, rotational coupler 110 and connector 177.

Sensor bundle 172 is further described as including a plurality of fibers, each having a sensing end and an emitting end arranged so that the sensing ends are disposed within fiber assembly 125 so that as substrate 180 passes over slit 130, each sensing end sweeps across substrate 180 such that the ensemble of sensing ends sweep over the entirety of substrate 180. Thus, the sensing ends form an array of data collection locations. In one embodiment, this array is preferably disposed substantially non-parallel to the direction of substrate motion.

FIG. 3 shows a simplified cross-sectional view of fiber assembly 125 prior to it being inserted into slit 130. Fiber assembly 125 has a nominally rectangular cross section with an active face 127 whose adjacent longitudinal edges are beveled to an angle α. The precise value of α is not important, and the beveled edged serve only to position fiber assembly 125 in slit 130. Face 127 may optionally comprise the optically transparent element 137 for allowing passage of light, whether reflected from the pad-contacting surface through the element to sensor bundle 172, or transmitted through the element from illuminator bundle 174. Transparent element 137 may be integral to fiber assembly 125, or it may be located elsewhere about the slit. Element 137 may comprise glass, plastic, water, an air gap, or any other transparent fluid or material suitable for the

purpose. In other embodiments, element 137 may be integral to, or comprise in whole or in part, platen 120 or polish pad 135. For example, the embodiment of FIG. 3 shows polish pad 135 having element 137 in the form of a rectangular window formed therein so that element 137 is aligned with slit 130.

Although illuminator bundle 174 includes many fibers, FIG. 3 shows only two representative illumination fibers, illumination fiber 310a having a termination end 194a and illumination fiber 330a having a termination end 194b. Likewise, sensor bundle 172 includes many sensor fibers, but FIG. 3 shows a single representative sensor fiber, sensor fiber 320a, which has a termination end 192a. Illumination fiber 310a and illumination fiber 330a extend from illuminator bundle 174 to face 127 of fiber assembly 125. Likewise, sensor fiber 320a extends from sensor bundle 172 to face 127 of fiber assembly 125. Termination end 192a is disposed between termination end 194a and termination end 194b.

In operation, light from light source 160 propagates through illumination fiber 310a in illuminator bundle 174 to termination end 194a and through illumination fiber 330a to termination end 194b, and is emitted from face 127 of fiber assembly 125. Some of the light reflected from substrate 180 enters sensor fiber 320a, which directs the light back to spectrometer 190 via sensor bundle 172.

FIG. 4A shows a top view of fiber assembly 125 (not to scale). Fiber assembly 125 has a length and a width, with the length being slightly longer than the diameter of substrate 180, e.g. 220 mm if designed for use with 200 mm wafers. The width is typically 1 to 5 millimeters. Illuminator bundle 174 connects to one side of the long dimension of fiber assembly 125 and sensor bundle 172 connects to the opposing side. FIG. 4 further shows a row of sensor fibers 320 disposed between a first row of illumination fibers 310 and a second row of illumination fibers 330.

Illumination fibers 310 and illumination fibers 330 are optical fibers. In a preferred embodiment, the fibers are plastic with a diameter of 0.75 mm, but fibers as large as 1 mm and as small as 0.05 mm also work.

Sensor fibers 320 are optical fibers with a preferred diameter of 0.100 mm and with a termination end having an area. Fibers with a larger diameter can be used, but with a loss of spatial resolution. Fibers with a smaller diameter can be used to increase spatial resolution, but the cost of assembly increases.

With continuing reference to FIG. 4A, illumination fibers 310 and illumination fibers 330 are oriented edge-to-edge along a straight line with a center-to-center spacing approximately equal to the fiber diameter. A distance approximately equal to the radius of the illumination fibers separates illumination fibers 310 and illumination fibers 330.

Illuminator bundle 174 includes several hundred fibers per row of fibers. The number of rows of illumination fibers 310 times the thickness of the individual illumination fibers should be approximately 1 mm or larger. Likewise, the number of rows of illumination fibers 330 times the thickness of the individual illumination fibers should be approximately 1 mm or larger. By way of example, illuminator bundle 174 requires approximately 300 fibers per row of fibers if the fibers have a diameter of 0.75 mm and are arranged edge-to-edge as shown in FIG. 4A. Thus, with two rows of illumination fibers, illuminator bundle 174 requires a total of 600 fibers. Examples of illumination fiber configurations that work include a single row of fibers having a thickness of 0.75 mm works, two rows of fibers having a thickness of 0.50 mm works, and five rows of fibers having a thickness of 0.20 mm. The number of illumination fibers 310 and illumination fibers 330 depends on the desired resolution of the image formed using the apparatus of the present invention. The resolution is also affected by the amount of light available to shine on substrate 180, and by the rotation rates of the carrier and of the platen, and to a lesser extent by R_{OFFSET}. By way of example, a preferred configuration involves approximately 600 illumination fibers and 300 sensor fibers with terminations 192a distributed along an overall length of 220 mm.

Sensor fibers 320 are on centers approximately equal to the desired resolution of the final wafer image. Overall image resolution depends in part on the number of sensor fibers 320 used to form sensor bundle 172. Increasing the number of sensor fibers increases resolution. In one embodiment, 300 sensor fibers 320 are used.

Sensor fibers 320 collect light from a cone having an apex at the termination end of each sensor fiber, and extending through window 137 in pad 135 to substrate 180. This cone has a numerical aperture (NA) of approximately 0.22, and forms a detection spot approximately 1 mm in diameter on substrate 180. Since measurements are made during an integration time and while substrate 180 is moving relative to sensor fibers 320, the actual area on substrate 180 that is being sensed is oblong, and is approximately 1.5 mm long. This portion of the substrate is sensed by light reflected from the detection spots corresponding to each sensor fiber, thereby providing a spatial field of detection spots that form a one-dimensional reflectance image. Thus, in one embodiment, data point spacing may be provided by the spatial field of detection spots the imaging system. The detection spots, and/or data points, may be spaced in an array that is substantially contiguous, or substantially non-contiguous. A substantially contiguous array of data points is one derived from an array of detection spots on a substrate 180 whereby a substantial number of adjacent detection spots touch at their borders, or overlap, such that a continuous, or nearly continuous image of an illuminated portion of the substrate may be detected. A substantially non-contiguous array of data points is one that is not substantially contiguous, i.e. one derived from an array of detection points where substantial pairs of adjacent detection points on a substrate 180 are separated, leaving some portion of the illuminated substrate undetected.

FIG. 4B shows the preferred location of sensor fibers 320 with respect to illumination fibers. By way of example, FIG. 4B shows representative illumination fiber 310a and illumination fiber 310b positioned side-by-side and opposed by illumination fiber 330a and illumination fiber 330b. Sensor fiber 320a is disposed between illumination fibers 310a and 310b and illumination fibers 330a and 330b.

Illumination fibers 310 and illumination fibers 330 serve several purposes. One, they provide a conduit for delivering sufficient light to substrate 180 that the light collected by sensor fibers 320 can be analyzed easily. Two, by providing multiple light sources for each individual sensor fiber, and in particular distributed light around each sensor fiber 320a as shown in FIG. 4B, any angular dependence of light sensed by the sensor fibers is averaged out. Third, by providing illumination sources that are

individually large compared to the size of the sensor fibers, any azimuthal dependence of light sensed by the sensor fibers is also averaged out. This combination is important to minimize the effect of light diffracting off structures in the surface of substrate 180.

The relatively large diameter of illumination fibers serves two functions. One, it serves to provide a large area illumination source that suppresses diffractive effects when light scatters from device features on substrate 180. Two, the amount of light collected by sensor fibers 320 depends in part on the distance between the sensor fiber termination (e.g. termination 192a) and substrate 180. This distance corresponds to the thickness of polish pad 135, which diminishes during polish. New polish pads have a thickness of approximately 2.4 mm, and are replaced when the polish pad thickness is approximately 1.5 mm. Each sensor fiber 192a receives light emitted from illumination fibers 310a, 310b, 330a, and 330b. By arranging for light to strike substrate 180 over an area large compared to the area of sensor fiber termination 192a, the light source behaves as an extended source regardless of the change in thickness of polish pad 135.

In operation, illumination fibers 310 and illumination fibers 330 emit light out of fiber assembly 125 and onto substrate 180. Some of the light reflected by substrate 180 enters sensor fibers 320, and propagates to spectrometer 190, which analyzes it.

FIG. 5 shows a line imaging spectrometer 511 that is part of spectrometer 190. Line imaging spectrometer 511 comprises a lens assembly 560, a diffraction grating 570, and a two-dimensional imager 580. The line imaging spectrometer operates as follows. Light from source 160 passes through illumination bundle 174, and impinges on a film contained on or in substrate 180. The light reflects off the wafer and is received by sensor bundle 172, which couples the light to lens assembly 560 that produces a line image of a corresponding line on substrate 180. The line image is arranged along a spatial dimension. The line image passes through diffraction grating 570. Diffraction grating 570 receives the line image and dissects each subportion thereof into its constituent wavelength components, which are arranged along a spectral dimension. In one implementation, the spectral dimension is perpendicular to the spatial dimension. The result is a two-dimensional spectral line image that is captured by two-dimensional

imager 580. In one implementation, the imager is a CCD, the spatial dimension is the horizontal dimension, and the spectral dimension is the vertical dimension. In this implementation, the spectral components at each horizontal CCD pixel location along the slit image is projected along the vertical dimension of the CCD array.

The line imaging spectrometer 511 in this example is manufactured by Filmetrics, Inc. (San Diego, California) the assignee of the subject application. In this spectrometer, transmission diffraction grating 570 is manufactured by Optometrics, (Ayer, MA), Part No. 34-1211. Two-dimensional imager 580 is a CCD imager incorporating a Model Turan line scan camera manufactured by Dalsa Inc., that has a CCD imager with 2048 pixels in the system spatial direction, and 96 pixels in the system spectral direction. Two-dimensional imager 580 is operated in area scan mode, with only the first 32 rows of pixels read out. Two-dimensional imager 580 is further configured to operate in an analog mode to generate the video signal. This results in a data read rate greater than 1000 frames per second. Thirty-two rows of spectral data are sufficient for measurement of thicknesses in the range required for layers polished by CMP tools.

If used with a single wavelength light source, two-dimensional imager 580 can be replaced with a one-dimensional imager. Though a one-dimensional imager is adequate for some applications where an especially low-cost whole-wafer imaging system is required, the loss of spectral information can lead to less precise and more ambiguous measurements of the film thickness and other wafer characteristics.

The numerical aperture of the lens 560 is approximately 0.06, which is considerably smaller than that of sensor fiber 320. By minimizing bends in sensor fiber 320 during assembly, the light propagating through sensor bundle 172 undergoes only minimal mixing, so that the detector senses light from a smaller cone angle than the numerical aperture of 0.22 of the sensor fibers 320 would indicate. Thus, the choice of NA of the lens 560 can be used to set the effective spot size of the individual sensor fibers.

With reference to FIG. 4, sensor fibers 320 are preferably arranged in a sequence (e.g. left to right) that matches the sequence of fibers at the other end of sensor bundle

174 in FIG. 5. This arrangement preserves the orientation of data points and facilitates data processing. However, such a pre-determined sequence is not necessary to practice the present invention. The sequence of sensor fibers 320 can be arbitrary and unknown to facilitate fabrication of fiber bundle 115 and sensor bundle 174. To determine the actual sequence of fibers 320, light shined through each individual sensor fiber 320 is detected on 2-dimensional imager 580, thereby creating a map of input light to detected light. Once measured, this map is saved, and all subsequent measurements sorted out using this map. Data point spacing provided by the spatial field of the sensor fibers can thus be properly reconstructed by system controller 108 during the imaging process, regardless of sensor fiber sequence at either end.

FIG. 6 shows a portion of a preferred method of fabricating fiber assembly 125. Fiber assembly 125 further includes plate 610 and plate 630, both of which have a thickness approximately equal to half the radius of illumination fibers 310 so that together they have a thickness slightly greater than the radius of illumination fibers 310. Plate 610 is patterned with parallel grooves 620 to a depth of approximately the radius of sensor fibers 320, as shown in FIG. 6A. Plate 610 and plate 630 are made of metal such as aluminum or stainless steel. Electropolishing is used to form grooves 620. Plate 610 and plate 630 can also be made of other materials, e.g. silicon (with grooves 620 formed using lithographic techniques and etching).

Once the grooves have been formed, sensor fibers 320 are positioned in grooves 620. Sensor fibers 320 are then secured in place using an epoxy-based adhesive (not shown). Referring to FIG. 6B, plate 630 is then positioned on top of sensor fibers 320 in grooves 620 of plate 610 and glued in place with epoxy (also not shown). Illumination fibers 310 are then positioned on the surface of plate 630 opposing grooves 625, and secured in place using epoxy, as shown in FIG. 6C. Then, illumination fibers 330 are positioned on the surface of plate 610 opposing grooves 620, and secured in place using epoxy. This portion of the assembly process results in an end-view configuration as shown in FIG. 6C, and in side view as shown in FIG. 6D. The fibers are then cleaved and polished so that fiber ends 192 and 194a and 194b are co-planar, as shown in FIG. 6E. Illumination fibers 310 and illumination fibers 330 are then bundled to form

illuminator bundle 174 using methods known in the art. Likewise, sensor fibers 320 are bundled to form sensor bundle 172.

FIG. 7 shows an alternate method of fabricating fiber assembly 125. Plate 610' and plate 630' are identical to plate 610 and plate 630 respectively, except that no grooves are formed. To obtain sensor fibers 320, sensor fibers 620 are positioned on plate 610', as shown in FIG. 7A, and secured in place using epoxy (not shown). Plate 630' is positioned on against sensor fibers 620 and secured in place using epoxy (not shown) , as shown in FIG. 7B. The rest of the assembly is identical to that shown in FIG. 6. Once assembled, periodic sensor fibers, e.g. every sixth fiber, is selected to form sensor fibers 320, as shown in FIG. 7C.

FIG. 8 shows method 800 for using the apparatus of the present invention for collecting and analyzing reflectance data from the surface of substrate 180. The method involves collecting a series of line images using spectrometer 190 as fiber assembly 125 sweeps under carrier 170 and substrate 180. The sequence of line scans resulting from fiber assembly 125 sweeping under substrate 180 constitutes a frame. Each rotation of platen 135 causes fiber assembly 125 to sweep under substrate 180 and produce additional frames. The sequence of frames, once suitably analyzed, provides a wealth of information about the polish process. For example, a single frame, or a combination of frames, may be used to construct a two-dimensional image of substrate 180.

The CMP system controller provides the rotation rate of platen 135, the rotation rate of carrier 170, and the angle reference signal. The angle reference signal constitutes a trigger signal, which, along with knowledge of the platen rotation rate, allows the whole-substrate imaging system 105 to initiate data collection just as fiber assembly 125 begins to pass beneath the leading edge of retaining ring 182 and to pause data collection just as fiber assembly 125 completes is sweep beneath substrate 180 and the trailing edge of retaining ring 182. Thus, the position of the substrate 180 is known; however the rotational position of substrate 180 on carrier 170 is not known.

Each series of line images includes spectral reflectance of the light from each sensor fiber 320. Since the position of each sensor fiber under the carrier 170 is known

(relative to platen 135, not with respect to any particular rotational position of carrier 170), a line image therefore comprises a set of reflectance measurements versus position along a curve that is approximately a chord across substrate 180. By collecting a sequence of line scans as fiber assembly 125 sweeps under substrate 180, spectral reflectance data for an entire wafer can be obtained in a single pass of fiber assembly 125 under substrate 180. Method 800 provides a way of collecting this spectral data in each frame, and re-mapping the spatial information to form an image of substrate 180 as a function of time. The image may thus comprise a two-dimensional image, having both a spatial dimension and a spectral dimension.

The spectrometer readout rate determines the sampling frequency. The platen rotation rate determines the amount of time fiber assembly 125 is under substrate 180, which when combined with the sampling frequency allows a user to select a suitable data density and hence image resolution. After collecting a set of line images collected during a single sweep, the data is corrected for the rotation of substrate 180 relative to platen 135. The result is an image, which can be analyzed to yield significant process information. The data, either raw or processed, can also be stored to allow whole-substrate imaging system 105 to generate time dependent images of substrate 180 during CMP. These images can also be analyzed to produce a wealth of valuable process information.

Initializing whole-substrate imaging system 105 involves obtaining initialization data from the CMP tool to set the basic operating parameters of whole-substrate imaging system 105. The initialization data includes the nominal carrier rotation rate, the platen rotation rate, R_{OFFSET} (and any programmed changes in R_{OFFSET}), and the angle reference signal. Controller 195 uses the angle reference signal to generate a start data acquisition signal so that data is collected only while fiber assembly 125 is beneath carrier 170.

In step 810, whole-substrate imaging system 105 acquires a sequence of line scans as fiber assembly 125 sweeps under carrier 170 holding substrate 180. Each line scan comprises a set of reflectance data from each of the sensor fibers 320 that make up sensor bundle 172. The sequence of line scans corresponding to a single sweep of fiber

assembly 125 under carrier 170 forms a frame. FIG. 9 shows this process, and in particular shows fiber assembly 125 in each of three positions as it sweeps under substrate 180. FIG. 9 further shows a trajectory 910 of sensor fiber 990 of fiber assembly 125.

This step further involves sensing how much light is being received by integrating light received by spectrometer 190, for example by determining whether the light falls between an acceptable minimum (meaning that there is sufficient light to make measurements) and a maximum (above which there is signal saturation). Then, if need be, the intensity of the light can be adjusted to provide a better signal to noise ratio. The intensity can be adjusted by changing the integration time or by changing the light intensity. Then, by knowing the platen rotation rate and the carrier rotation rate, a transit time can be calculated. This transit time corresponds to the time taken by fiber assembly to sweep under retaining ring 182 and substrate 180. The transit time can also be determined empirically. One such way to determine the transit time empirically is to examine the reflectance measurements of sensor 990 as it follows trajectory 910. Since the reflectance measurements from retaining ring 182 differ from those of substrate 180, the actual time to traverse trajectory 910 beneath substrate 180 and retaining ring 182 can be determined. Whether using a calculated transit time or an empirically determined transit time, the transit time is then divided by a measurement sampling rate to deduce a number of line scans per frame. This step determines the data density.

Step 820 involves determining which frame contains the center point of substrate 180, which is necessary to enable the substrate image to be properly oriented. This step is also essential to allowing whole-substrate imaging system 105 to monitor specific sites on a wafer. Again referring to FIG. 9, each frame includes a line image extending across substrate 180. For simplicity, FIG. 9 shows fiber assembly 125 having fewer sensors than would be used in practice. To facilitate the explanation of method 800 and the operation of whole substrate imaging system 105 only twelve sensors are shown even though in practice the apparatus of the present invention benefits from the presence of many more sensors.

Each line image includes a signature portion corresponding to the reflectance of retaining ring 182. As fiber assembly 125 sweeps under carrier 170, reflected light collected by sensor bundle 172 includes at first only light reflected from retaining ring 182, which indicates the edge of carrier 170. Once fiber assembly 125 is positioned under substrate 180, one or more sensor fibers collect reflected light from substrate 180 as well as signature light from retaining ring 182. FIG. 9A shows an example of fiber assembly 125 just after it has passed under the leading edge of retaining ring 182 so that some sensor fibers are positioned beneath retaining ring 182 and other sensor fibers are beneath substrate 180. In particular, sensor 940 and sensor 930 collect light from retaining ring 182 while the sensors between them, including sensor 920, collect light reflected from substrate 180. In FIG. 9A there are 7 sensors that collect light from substrate 180.

In FIG. 9B shows the position of fiber sensor 125 at a slightly later time than in FIG. 9A. Sensor 960 and sensor 950 collect signature light from retaining ring 182. Ten sensors, including sensor 930, sensor 970, and all of the other sensors between sensor 930 and sensor 970 collect light reflected from substrate 180. In FIG. 9C shows the position of fiber sensor 125 at a slightly later time than in FIG. 9B. In FIG. 9C, sensor 930 and sensor 940 collect signature light from retaining ring 182. Seven sensors, including sensor 920, sensor 980, and all of the other sensors between sensor 920 and sensor 980 collect light reflected from substrate 180.

Thus, as fiber assembly 125 sweeps across substrate 180, more and more sensors collect light reflected from substrate 180 up to a maximum, then fewer and fewer do so until fiber assembly 125 passes under the trailing edge of retaining ring 182. By determining the maximum number of sensors that collect light reflected from substrate 180 in the collection of line scans that comprises a frame, the line scan closest to the center of substrate 180 can be identified. The midpoint of reflectance measurements corresponding to reflectance off substrate 180 and between the signature reflectance measurements of this line scan corresponds to the center of substrate 180. Each frame is labeled with a frame number to allow a time ordering of frames.

Step 830 uses knowledge of the platen rotational speed and knowledge of the location of the carrier center from Step 820 to predict the wafer center in each frame. The calculations involved in Step 830 use coordinate transformations that are well known in the art.

Step 840 combines knowledge of the frame number, the carrier rotation speed, and the location of the wafer center from Step 830 to un-rotate substrate 180. This step is necessary because between each line scan substrate 180 rotates, which distorts the image and must be corrected. As in Step 830, coordinate transforms that are well known in the art are used to accomplish this un-rotation. Proper application of Step 830 and Step 840 yield a round wafer image when substrate 180 is round, as is the case when planarizing semiconductor wafers.

Step 850 uses well-known image processing techniques to clean up the spectral data for each sensed location. The "dark" response is subtracted, the image is scaled to the correct size so that it fits in the display area, and averaging techniques used to smooth roughness in the spectral profiles. One general averaging technique is to use box-car averaging on the spectral data for each pixel of two-dimensional imager 580. For reflectance data from metal surfaces, one specific averaging technique is to average all of the spectral data within a pre-determined wavelength range, and repeat this process for all the sensed locations. In one embodiment, the pre-determined wavelength range is chosen to encompass the entire range of sensitivity of two-dimensional imager 580. In another embodiment, the pre-determined wavelength range is chosen to encompass only a portion of the entire range of sensitivity of two-dimensional imager 580. Such a technique can be used to minimize, or even eliminate, reflectance variations caused by interferometric effects of underlying layers. In yet another embodiment, the pre-determined wavelength range is chosen to encompass only a very small portion of the entire range of sensitivity of two-dimensional imager 580, namely that sensed by a single pixel. This embodiment corresponds to using a single wavelength source of light.

This step further involves rotating the image to orient the notch (in the case substrate 180 is a semiconductor wafer) to a preferred orientation, either notch up, notch

down, notch left, or notch right. One way to orient substrates involves detecting the notch in the acquired wafer image. With approximately 300 sensor fibers 320 sweeping across substrate 180 with a typical sampling rate of 1 kHz, features as small as 1 mm can be detected. Since the notch on semiconductor wafers is approximately 2.5 mm by 2 mm, it is readily detected using techniques well known in the art. By comparing the expected substrate orientation from frame-to-frame with the measured orientation, substrate slippage can be detected and quantified modulo 2π.

Step 860 involves analyzing the spectral images to extract additional information. The type of additional information depends in part on the material being polished, i.e., metal or dielectric. The type of additional information also depends on the intended use of the additional information. For example, for endpoint detection applications, it is essential to learn as quickly as possible when to terminate a given process (or process step). For process control applications it is important to monitor the performance of a given CMP tool, and to provide corrections to CMP tool process parameters if needed. For polish control applications, it is important to ensure minimal non-uniformity and correct remaining film thickness upon the conclusion of a CMP process, and to know what the non-uniformity and remaining film thickness is at the end of a polish process.

In the case of metal layers being polished, it is very useful to know whether there is any residual metal, and if so where it is. One technique for assessing the presence of residual metal is to compare the average reflectance within a pre-determined spectral range to a threshold value for each sensed location across substrate 180.

FIG. 10 shows an example image 1010 of a partially processed silicon substrate during a CMP process. The substrate used for this example is made of silicon, and has been partially processed to include the deposition of copper film. During the CMP process, the bulk of the copper film must be removed so that residual metal forms desired conductive paths. One essential characteristic of the CMP process is that all residual metal be removed. FIG. 10 shows several regions 1020 that have not cleared. The trajectory of any single sensor across the substrate would not necessarily have traversed any of the uncleared regions. Because the apparatus of the present invention scans the

entire substrate, a significantly more reliable assessment of the status of the CMP process is possible.

Assessing dielectric film stacks is more complex due to the variation in spectral response as the thickness changes as well as the variety of film stacks that can contribute to any given reflectance measurement. One technique for dealing with dielectric films is to select one particular film stack present on a substrate, and compare measured reflectance with a calculated reflectance for a given top layer thickness by calculating a fitting parameter, for example, using such known techniques as least-squares. By varying the thickness of the top-most layer in the calculated reflectance and looking for a minimum in the least squared fit, the actual thickness can be determined.

Because there are thousands of measurements made over the entire substrate, many options exist. Measurements can be made at specific sites on substrate 180, using site coordination information provided to computer 160 of whole-substrate imaging system 105 via rotating coupler 110. Such sites can correspond to specific die, or they can correspond to well known measurement maps such as a polar map or Cartesian maps with 49 (or other) sites. Measurements using the apparatus of the present invention can also be used to determine such significant process performance characteristics as non-uniformity. Although such measurements are typically performed only after the completion of a CMP step, being able to report non-uniformity in addition to residual film thickness upon the completion of a CMP step is highly advantageous.

An additional analysis step that the present invention allows is the determination of significant process metrics such as remaining film thickness in specific, pre-determined regions on substrate 180, and communicating such metrics to the CMP system controller during a CMP polish process. This capability is particularly advantageous for multi-step CMP processes such as those used to polish copper films. These processes can include different process recipes, including different slurries, depending on the metal film being polished. Thus, whole-substrate imaging system 105 is used to detect the clearing of one metal, e.g. copper, which exposes a barrier film such as tantalum. For this situation, whole-substrate imaging system 105 measures the

clearing of the copper film, communicates this clearing to the CMP system controller, then continues to monitor the CMP process while the tantalum is polished.

The present invention can also be used as part of a feedback control system, especially when used with carriers that have one or more pressure zones and the ability to adjust the pressure within a given zone according to need. To implement such a feedback control system, the CMP system controller communicates site location information to whole-substrate imaging system 105 via rotational coupler 110. Whole-substrate imaging system 105 then measures substrate 180, identifies sites on substrate 180 that coincide with the site location information, and reports via rotational coupler 110 the metrics for the desired sites. The CMP system controller then adjusts tool parameters such as zonal pressure to improve process performance. This process can be applied while polishing a substrate, or it can be applied in a run-to-run mode by using measurements on one substrate to affect polish parameters on a following substrate.

Step 870 involves storing data and assessing whether the process is complete or not. If the process is complete, then method 800 ends. If the CMP process is not complete, then the logic of method 800 moves to step 810, i.e., more reflectance data is collected.

WHOLE DIE IMAGING SYSTEM

It will be apparent to those of ordinary skill in the art that the system of the present invention can be used to image, during CMP processing, portions of a substrate that are less than an entire substrate. The result is a set of data corresponding to one or more swaths across substrate 180. A swath is the portion of substrate 180 being sensed; a data swath is the optical data obtained from the swath. In this embodiment it is advantageous that each swath have a width that is at least as large as the die on the substrate. By analyzing such swaths, individual die can be identified and the orientation of substrate 180 can be determined. Furthermore, individual sites within die can be measured and the CMP system controller informed of such measurements.

Streets are non-used portions of substrate 180 between integrated circuits on substrate 180. An integrated circuit surrounded by streets forms a die. Though each die is rectangular in shape, die can also be made in squares. Although planar die have symmetry (two-fold for rectangular die and four-fold for square die), die containing integrated circuits typically do not have symmetry because each die contains functional elements that lead to a non-uniform visual appearance that can be detected.

With reference to FIG. 11, whole die imaging system 105' includes a slit 130' formed in platen 120 so that the length of slit 130' is less than the diameter of substrate 180. A fiber assembly 125' disposed within slit 130 is arranged along a radial line extending from rotational coupler 110. Polish pad 135 has a window 137' that is smaller than substrate 180, and that serves to allow light to be emitted from fiber assembly 125' and subsequently received by fiber assembly 125' upon reflection from substrate 180. The other elements in FIG. 11 are otherwise identical to those in FIG. 1. FIG. 12A shows the nominal position of fiber assembly 125' in slit 130', and arranged so that in normal operation, fiber assembly 125' passes under or nearly under the center of substrate 180. FIG. 12 is otherwise identical to FIG. 2.

Fabrication of fiber assembly 125' is identical to that of fiber assembly 125 except that the overall length of fiber assembly 125' is chosen to be approximately as large as, or slightly larger than, the size of the die on substrate 180. In one embodiment, fiber assembly 125' has a length of 20 mm, corresponding to approximately 27 sensor fibers if the sensor fibers are located on .73 mm centers. Whole die imaging system 105' produces two-dimensional arrays of 10x10 to 20x20 data points are obtained, depending on die size.

FIG. 13 shows an example of fiber assembly 125' sweeping along a trajectory 1310 that passes under retaining ring 182 and substrate 180 to form swath 1320. Swath 1320 further includes a transverse dimension 1325 that is approximately equal to the length of fiber assembly 125'. Substrate 180 further includes many complete die 1330 and may also include partial die 1340.

Die 1330 include partially processed integrated circuits and un-used portions of substrate 180 that surround the partially processed integrated circuits. A multiplicity of streets 1350 and transverse streets 1355 separate adjacent integrated circuits.

Partial die 1340 are portions of partially processed integrated circuits that serve to facilitate the fabrication of adjacent die, but are otherwise non-functional.

In operation and with continuing reference to FIG. 11, substrate 180 loaded into carrier assembly 170 is pressed into polish pad 135 while carrier assembly 170 rotates about axis of rotation 155, platen 120 rotates about axis of rotation 150, and slurry flows across polish pad 135. A combination of chemical and mechanical processes abrades material from the surface of substrate 180, i.e., from die 1330 and partial die 1340. While the polishing process takes place, optoelectronic assembly 115 generates light based on the power and control signal generated by the variable power supply generator within system controller 108. This light passes through optical illuminator bundle 174 to fiber assembly 125', where it illuminates wafer 180 as slit 130' passes under wafer 180. Fiber assembly 125' also receives light reflected from wafer 180, and directs this reflected light into sensor bundle 172. Optoelectronic assembly 115 receives the reflected light and converts it into the video signal than can be converted into an image of a portion of substrate 180 by system controller 108.

Analysis of data uses method 1400 shown in FIG. 14. Method 1400 is identical to method 800 with the exception that portion of Step 850 that involves determining substrate orientation by identifying the location of the notch must be replaced by Step 1450 since an arbitrary swath does not necessarily include the notch.

Step 1450 uses well-known image processing techniques to clean up the spectral data for each sensed location. The "dark" response is subtracted, the image is scaled to the correct size so that it fits in the display area, and averaging techniques used to smooth roughness in the spectral profiles. One general averaging technique is to use box-car averaging on the spectral data for each pixel of two-dimensional imager 580. For reflectance data from metal surfaces, one specific averaging technique is to average all of the spectral data within a pre-determined wavelength range, and repeat this process for all

the sensed locations. In one embodiment, the pre-determined wavelength range is chosen to encompass the entire range of sensitivity of two-dimensional imager 580. In another embodiment, the pre-determined wavelength range is chosen to encompass only a portion of the entire range of sensitivity of two-dimensional imager 580. Such a technique can be used to minimize, or even eliminate, reflectance variations caused by interferometric effects of underlying layers. In yet another embodiment, the pre-determined wavelength range is chosen to encompass only a very small portion of the entire range of sensitivity of two-dimensional imager 580, namely that sensed by a single pixel. This embodiment corresponds to using a single wavelength source of light.

Since the location of the notch is not known, wafer orientation is determined using swath data. Edge detection techniques, well known in the art, are used to orient the substrate modulo $\pi/2$, as shown in FIG. 15A. Note that actually presenting an image of swath 1320, as shown in FIG. 15A is not necessary, but it is necessary to know the orientation of streets 1350 and transverse streets 1355 within the swath data.

To determine the orientation of substrate 180, a die 1360 in swath 1320 is examined for optical non-homogeneities. Since integrated circuits are not homogeneous, the light reflected from them is also non-homogeneous. Thus, light reflected from some portions of die 1360 have differences compared to other portions of die 1360. One example of a difference is a color difference due to one portion having more metallization lines or being composed of materials having different optical properties and thicknesses. A second difference is an intensity difference due for example to more metal in one portion than other portions. Such differences in intensity can also be due to different absorption occurring within one portion of die 1360 compared to a different portion. A third difference arises by combining the first two differences, i.e., examining the intensity of light in a narrow wavelength region corresponding for example to a null region where light interferes destructively, thus giving a dark appearance. The choice of wavelength for examining reflected light depends on the optical properties of the film stack being examined, and this wavelength can be varied during the polish process. When polishing metal layers where the reflectance is nearly uniform until the metal layer is only a few hundred nanometers thick, intensity variations are preferred.

One way to examine the light reflected within die 1360 is to partition the light from die 1360 into quadrants, as shown in FIG. 15B, and to compare the intensity of light within each quadrant. So long as one quadrant is either brighter or dimmer than the other quadrants, as represented by a spot 1380, the orientation of substrate 180 is determined uniquely.

One way to enhance the reliability of detecting substrate orientation is to examine more than one die. Examining more than one die also provides information about the polishing uniformity of the CMP process.

Depending on the length of fiber assembly 125' and the dimensions of die 1360 (which may differ as manufacturing needs change), swath 1330 may not necessarily include an entire die. In this case it is advantageous to detect streets, using techniques known in the art, and to compare the light reflected from quadrants surrounding an intersection 1370 of a street and a transverse street, as indicated by a spot 1382 in FIG. 15C. Since the die-to-die reflectance pattern is nominally the same, substrate orientation is determined uniquely once spot 1382 is located. With this technique it is not necessary that the length of fiber assembly 125' exceed the length of die 1360, i.e., it is not necessary that an entire die 1360 be imaged to determine the orientation of substrate 180, which significantly enhances the flexibility of the present invention. This technique requires only that sufficient sensor fibers 320 be included in fiber assembly 125' that intersection 1370 be identifiable and that the portions of die surrounding intersection 1370 be large enough that optical reflectance differences can be detected.

It will be apparent to those of skill in the art that fiber assembly 125' can be formed in more than one section to allow two or more swaths across substrate 180 to be sensed. It will also be apparent to those of skill in the art that if fiber assembly 125' is formed in more than one section that each section can be disposed within platen 120 at different angles to allow carrier 170 to partially rotate substrate 180 between measurements, thus ensuring that sequential swaths within a single platen revolution are approximately perpendicular to each other (or at another angle with respect to each other if desired). (In this embodiment, additional windows 137' in polish pad 135 are also

necessary.) Since carrier rotation rates are often nearly the same as platen rotation rates, displacing a first portion of fiber assembly 125' from a second portion of fiber assembly 125' by 90 degrees yields nearly perpendicular swaths.

If the length of transverse dimension 1325 is sufficiently small then fiber assembly 125' can be modified by replacing sensor bundle 172 with an optical assembly 1640 that couples light reflected from the surface of substrate 180 directly to line imaging spectrometer 1611.

FIG. 16 shows a line imaging spectrometer 1611 that is part of spectrometer 190. Line imaging spectrometer 1611 is identical to line imaging spectrometer 511 except that sensor bundle 172 is replaced with lens assembly 1640. Line imaging spectrometer 1611 further comprises a lens assembly 560, a diffraction grating 570, and a two-dimensional imager 580. Line imaging spectrometer 1611 operates as follows. Light from source 160 passes through illumination bundle 174, and impinges on a film contained on or in substrate 180. The light reflects off the wafer and is received by sensor bundle 172, which couples the light to lens assembly 560 that produces a line image of a corresponding line on substrate 180. The line image is arranged along a spatial dimension. The line image passes through diffraction grating 570. Diffraction grating 570 receives the line image and dissects each subportion thereof into its constituent wavelength components, which are arranged along a spectral dimension. In one implementation, the spectral dimension is perpendicular to the spatial dimension. The result is a two-dimensional spectral line image that is captured by two-dimensional imager 580. In one implementation, the imager is a CCD, the spatial dimension is the horizontal dimension, and the spectral dimension is the vertical dimension. In this implementation, the spectral components at each horizontal CCD pixel location along the slit image is projected along the vertical dimension of the CCD array.

Since the apparatus of the present invention provides for many reflectance measurements within a die, selected sites within the die can be monitored during the CMP process, thus providing valuable information about changes in the surface of substrate 180 as it is being polished. The apparatus of the present invention can monitor

film thickness (when polishing dielectric materials), within-substrate uniformity, die-to-die uniformity, and dishing. All of this process information is communicated to CMP system controller via system controller 108.

While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible that are within the scope of this invention.